5 Economic and Societal Benefits of Soil Carbon Management: Cropland and Grazing Land Systems

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CONTENTS

INTRODUCTION

The purpose of this chapter is to provide both a historic perspective of U.S. land use as well as to address the role of agricultural technologies to enhance soil carbon

(C) management and how these are economically and environmentally beneficial. Increasingly soil C sequestration is linked to its role in helping to mitigate inputs of carbon dioxide (CO_2), a greenhouse gas (GHG), into the atmosphere, a role becoming extensively documented in the literature. The process includes the uptake of atmospheric CO_2-C by photosynthesis and the subsequent sequestration of the C contained in the plant materials into the soil as soil organic carbon (SOC). Additionally documented is that SOC is lost as a result of improper soil management or potential alternative uses of C resources that could otherwise be returned to the soil.

Soil C sequestration is worthwhile for many reasons, and in sequestering C, both improved soil productivity and environmental services can result. Soil contains the world's largest terrestrial C pool, and there is a direct link between soil and atmospheric C. Misused soils are a major source of CO_2. Practices and policies that encourage maintaining and improving soil C sequestration can consistently be associated with improved soil and water quality, reductions in silt loads and sedimentation into streams, lakes, and rivers, as well as improvements in air quality (Lal, Follett, and Kimble, 2003). Programs, such as the Conservation Reserve Program (CRP) and other incentive programs, generally improve the aesthetic and economic value of land while also enhancing the biodiversity of either the immediate land parcel or of surrounding areas.

A recent estimate of the potential for soil C sequestration in the United States is 288 million megagrams (MMg = Tg) C yr^{-1} or 1056 MMg atmospheric CO_2 yr^{-1} (Lal, Follett, and Kimble, 2003). This potential for the removal of atmospheric CO_2 and its subsequent sequestration as soil C approximates about 15% of the total U.S. emissions for 2000 of 1887 MMg of CO_2-C GHG equivalents yr^{-1} (US EPA, 2002). Our discussion here will focus on cropland and grazing land with their potential SOC sequestration ranges of 48–98 MMg C yr^{-1} and 13–70 MMg C yr^{-1}, respectively within the United States (Lal, Follett, and Kimble 2003). Together, cropland and grazing land account for approximately 40% of the U.S. potential for C sequestration. The following discussion will also include background information about how soil C stocks have been degraded, where we are now with C stocks in the United States, and how the building of C stocks needs to be addressed to approach the potential amounts that might be sequestered. Important to this discussion is how attaining such additional stocks of SOC would provide societal and economic benefits in the United States. However, SOC stocks cannot be considered alone because of the importance of inputs of crop residue-C resources to the soil, the losses of SOC through mismanagement of soils, the role of government programs, and emerging alternative uses of crop residue C (or other organic C wastes generally returned to soils). These all affect SOC sequestration and the potential of U.S. agricultural soils to sequester C. Increasing current SOC stocks by nearly approaching the potential rate of SOC sequestration cannot be realized without greater adoption of recommended management practices (RMPs). Alternatively, the removal of crop residues from agricultural lands can increase the likelihood that SOC stocks will decrease. Current estimates of rate of SOC sequestration for cropland (Intergovernmental Panel on Climate Change [IPCC] methodology; IPCC/UNEP/OECD/IEA, 1997) are that only about 20% of the potential rate of C sequestration is occurring (Sperow et al.,

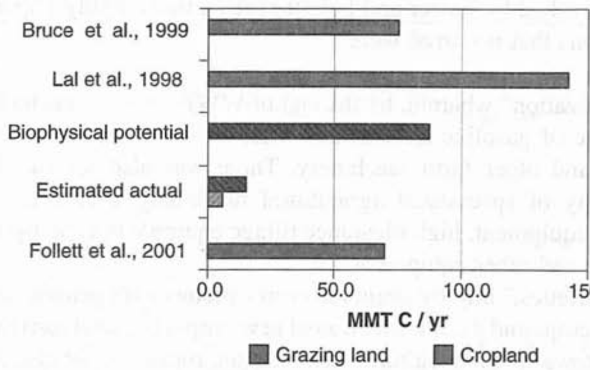

FIGURE 5.1 Estimates of SOC sequestration in U.S. croplands and grazing lands.

2003). However, when the IPCC methodology was also used to make a "biophysical" estimate, but with similar RMPs to those of Bruce et al. (1999) and Lal et al. (1998, 2003), Sperow et al. (2003) obtained estimates of potential soil C sequestration similar to those of the other authors (Figure 5.1). The IPCC methodology also results in very low estimates of SOC sequestration for grazing lands and therefore likely represents a reduced percentage of the potential soil C that can be sequestered there as well.

U.S. CROPLAND

A Brief History of U.S. Cropland Use

Following the end of the Civil War in 1865, westward population movement and population growth was increasingly dynamic. Westward movement of the U.S. population was aided by the Homestead Act of 1862 and by completion of the transcontinental railroad in 1869. Native American lands that had been seized by the government and their availability for settlement drew European immigrants whose numbers, coupled with the movement of U.S. citizen settlers increasingly opened the Great Plains and the western United States to agriculture. In 1870 and with a total population of 38.5 million people, the "center of the U.S. population" was in Highland County, Ohio, near present day Hillsboro. "Center of Population" is defined as the point at which an "imaginary, flat, weightless, and rigid map of the United States would balance perfectly" if every person – counted where they lived on the day of the census – weighed the same (U.S. Census Bureau, 2000). By 1940, with a population of 131.4 million, the "center" was in Sullivan County, Indiana, near Paxton, and by 2000, with a U.S. population of 281.4 million, it was in Phelps County, Missouri, near Edgar Springs.

Historical records also show that from the 1870s until about 1940 grain produced per unit of land area in the United States were essentially static but, depending upon the crop, yield increases after 1940 were from 75–400% (Allmaras et al., 1998; NASS, 2004). Following the shock of the 1930s "Dust Bowl," and after 1940, major subsequent technological innovations and a national response to the dust bowl occurred. As described by Power and Follett (1987), three highly important technological innovations that occurred were:

1. "Mechanization" wherein, by the end of WWII, most farms had switched to the use of gasoline tractors and there was an increase in the size of tractors and other farm machinery. There was also increased use and availability of specialized agricultural machinery, including combines, planting equipment, high-clearance tillage equipment, center-pivot irrigation rigs, and other equipment.
2. "Crop varieties," improvements in crop varieties with genetic advances in existing crops and the introduction of new crops (i.e., soybean) that pushed farmers toward "monocultures," and limited rotations, but also resulted in increased "crop-specific" knowledge by farmers about optimizing the yields that they could obtain.
3. "Agricultural chemicals," the use of "chemicals" as typified by manufactured nitrogen (N) fertilizer that was prominent after WWII and expansion of the use of agricultural pesticides.

These three technological advances after 1940 led farmers to increasingly grow a single or only a few crops and the development of increased confidence by farmers that with the use of the technologies described previously, the crops they grew would flourish.

Coupled with the preceding three technologies is a fourth technology that must also be included and that will be referred to as "improved soil management" (reduced tillage and enhanced crop residue management, etc.). Part of the national response to the Dust Bowl crisis of the 1930s, was the formation of the Soil Conservation Service (now the Natural Resources Conservation Service). The Dust Bowl provided a hard lesson about the use of large-scale, improper soil management, that when coupled with drought had devastating effects upon a nation and its society. This awakening did much for the conservation movement in the United States. As Historian Robert Worster wrote, "The ultimate meaning of the dust storms of the 1930s was that America as a whole, not just the plains, was badly out of balance with its natural environment" (PBS, 2006). The awful and worsening drought conditions, coupled with the horrible effects of the Great Depression, eventually meant that millions of U.S. citizens could no longer make a living from farming. By 1940, over 2.5 million people had moved out of the Great Plains. Life was simply unsustainable for many. Conversely, good land and resource management, and though not directly recognized at the time — good soil C management, has since been shown to restore the productivity of the land and the quality of the water and to conserve and help restore what were no doubt the previous major losses of SOC.

The lessons of the 1930s and 1940s resulted in greater awareness of the need for "soil conservation practices" and land set aside programs, which would conserve land and soil productivity, and increase soil C. Land under the "Soil Bank Act" of 1956 was set aside primarily to divert cropland from the production of major crops and thus to decrease agricultural inventories, but with a second purpose of establishing protective vegetative cover on land that needed conservation practices. Over

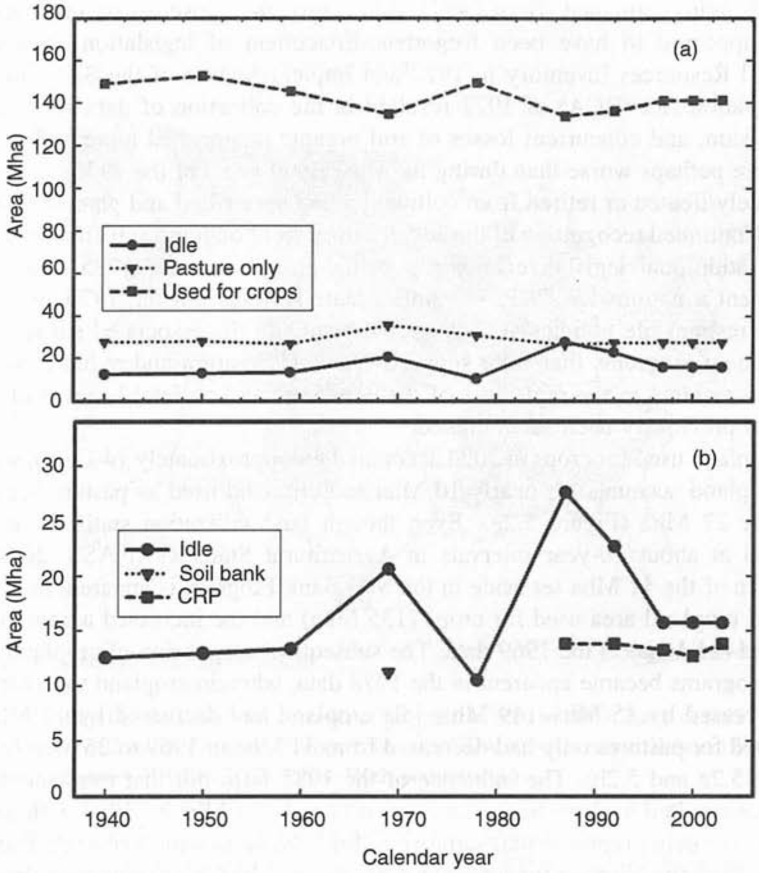

FIGURE 5.2 (a) U.S. cropland use. (b) U.S. idle and other cropland use from 1940. (From National Agricultural Statistics Service (NASS), Agricultural Statistics, NASS of USDA, U.S. Government Printing Office, Washington D.C., pp. IX–6, 2004. With permission.)

its 10-year life, the "Soil Bank Program" diverted 11.6 Mha (million hectares) or about 28.7 million acres to conservation practices on 306,000 farms. The Soil Bank Program was followed by two similar long-term contract programs: the Cropland Conservation Program, authorized in 1962, and the Cropland Adjustment Program, enacted in 1965.

In the early and mid-1970s, the prices of farm commodities rose significantly, due to diminished stocks and increased export demand. With the encouragement of the United States Department of Agriculture (USDA) policy makers U.S. producers responded by planting crops on marginal cropland and by also breaking out and planting range and pasture lands (Figure 5.2). This activity continued until the early 1980s, when overproduction and a strengthening U.S. dollar depressed prices, causing farm income to fall to its lowest level since the 1930s. However, because of unprecedented foreign grain sales, all USDA-subsidized cropland-retirement programs were suspended by 1973, and eventually few enduring resource conservation benefits remained (Berg 1994). Amazingly, the conservation lessons of the 1930s appeared to have been forgotten. Enactment of legislation creating the National Resources Inventory in 1972 and implementation of the Soil and Water Conservation Act (RCA) of 1977 resulted in the collection of data showing that soil erosion, and concurrent losses of soil organic matter, had increased to levels that were perhaps worse than during the Dust Bowl years of the 1930s. Soils once adequately treated or retired from cultivation had been tilled and planted to annual crops. Continued recognition of the adverse impacts of ongoing soil erosion resulted in key additional legislative authority being placed into the 1985 farm bill to implement a nationwide CRP. The unfortunate lesson from the 1970s is that the lack of responsible policies at the national level and the associated suspension of government programs that were supportive to conservation and reduced soil degradation resulted in the rapid loss of the economic and societal benefits of soil C that had previously been accumulated.

Cropland used for crops in 2003 accounted for approximately 140 Mha, whereas idle cropland accounts for nearly 16 Mha and cropland used as pasture accounted only for 27 Mha (Figure 5.2a). Even though land utilization statistics are only reported at about 10-year intervals in Agricultural Statistics (NASS, 2004), the influence of the 11 Mha set aside in the Soil Bank Program is apparent in both the lowered cropland area used for crops (135 Mha) and the increased amount of idle cropland (21 Mha) in the 1969 data. The subsequent suspension of cropland retirement programs became apparent in the 1978 data, wherein cropland used for crops has increased by 15 Mha–149 Mha; idle cropland had decreased by 10 Mha and land used for pastures only had decreased from 31 Mha in 1969 to 26 Mha by 1978 (Figure 5.2a and 5.2b). The influence of the 1985 farm bill that implemented the CRP has resulted in there being contracts on nearly 14 Mha by 1987 with 28 Mha of idle land being reported that same year. Initially, an administrative decision was made to limit the criterion for acceptance of land into the CRP to control soil erosion. However, because of amendments to the CRP in the 1990 farm bill, environmental benefits were expanded so that state water quality areas, conservation priority areas, and public wetland protection areas were also included. Thus, by 1992, there were just over 13.8 million ha (34 million ac) of land under CRP contract and of those 7.2 million ha (17.8 million ac) were identified as highly erodible cropland by 1982, before the CRP was implemented (Figure 5.3).

As the CRP program and other conservation programs have continued they are resulting in numerous conservation and societal benefits (ERS, 2005). As outlined in their recent Fiscal Year Summary, the Farm Service Agency (FSA) (2004) indicates that in 2003, CRP reduced soil erosion by 400 MMg, and this reduction contributes directly to:

1. Improved water quality from less movement of sediments, nutrients, and other chemicals into streams, lakes, and rivers
2. Creation of 1 Mha of conservation buffers to protect fragile resources
3. Nearly 1 Mha of restored wetlands
4. 7 Mha of vegetative cover defined as best suited for wildlife habitat
5. 1.5 Mha of sensitive wildlife ecosystem restorations

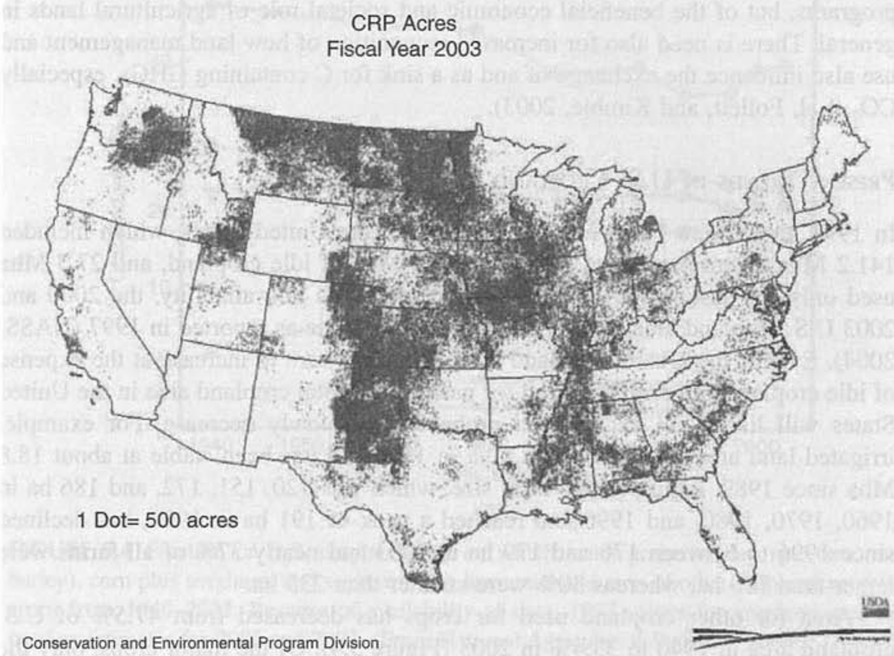

FIGURE 5.3 Land in the conservation reserve program (CRP) in 2003. Each dot on the map is equivalent to 202 ha (500 acres). (From FSA of USDA, Conservation Reserve Program, Fiscal Year Summary 1999 to 2003, 2004. With permission.)

Follett et al. (2001b), in a regional study extending across 5.6 Mha in the U.S. Great Plains and Western Corn Belt, identified that CRP had stored 5 MMg C. The FSA (2004) report estimates that 17 MMg C are stored in the soil and vegetation of U.S. land in the CRP in 2003. The CRP is an example of a government program supportive of conservation and the restoration of economic and societal benefits of soil C on the affected lands. In its first 20 years, CRP's societal contributions are substantial. It prevents 450 million tons of soil from eroding each year (Lasseter, 2006). The CRP and the related federal/state partnerships of the Conservation Reserve Enhancement Program help protect basic and vital natural resources by stopping soil and nutrients from washing into waterways or contaminating our air. It has already restored 1.8 million acres of wetlands. Drinking water is safer for millions of people, dust is reduced and air is more breathable, lakes are cleaner for swimming and fishing, and there are more fish, ducks, and other wildlife as a result of more abundant and improved habitat. As CRP contracts expire in the future, the farm and environmental communities have concerns about the implications if policy makers choose to end the program. Should the CRP program be discontinued there is need for information about the obvious impacts on soil erosion control, water quality protection, and wildlife habitat; and about benefits that may be lost, but that are not yet fully understood. The knowledge and efforts to continue with policies that have strong conservation and societal benefits must be sustained, and now extended, to recognize the role of not only the CRP or other soil conservation programs, but of the beneficial economic and societal role of agricultural lands in general. There is need also for increased recognition of how land management and use also influence the exchange of and as a sink for C containing GHGs, especially CO_2 (Lal, Follett, and Kimble, 2003).

Present Trends in U.S. Cropland Use

In 1997, there were 184.3 Mha of cropland in the United States, which included 141.2 Mha of cropland used for crops, 15.7 Mha of idle cropland, and 27.3 Mha used only for pasture (NASS, 2004). Because of its unavailability, the 2000 and 2003 U.S. cropland area will be estimated as the same as reported in 1997 (NASS, 2004). Even if the area of cropland used for crops were to increase at the expense of idle cropland and cropland used for pasture, the total cropland area in the United States will likely not expand and probably will slowly decrease. For example, irrigated land area peaked at 20.6 Mha in 1980 and has been stable at about 18.8 Mha since 1989. Even average farm size, which was 120, 151, 172, and 186 ha in 1960, 1970, 1980, and 1990 and reached a peak of 191 ha in 1996, has declined since 1996 to between 176 and 179 ha in 2003 and nearly 37% of all farms were larger than 700 ha, whereas 30% were smaller than 235 ha.

Area for other cropland used for crops has decreased from 47.5% of U.S. cropland area in 1940 to 33.4% in 2003 (Figure 5.4). Of the major crops, only the harvested area of soybean is showing a consistent increase in its fraction of U.S. cropland area from 1.3–20.7% (1.9–29.3 Mha) during 1940–2003 (Figure 5.4). The combined harvested area of rye, oats, and barley has decreased from 28.6% in 1940 to 17.2% in 2003 (21 Mha–4.3 Mha). The fraction of U.S. cropland harvested for wheat grain has remained fairly steady at 14.5% (21.6 Mha) in 1940 and 15.2% (21 Mha) in 2003. Area of harvested sorghum was 1.7% (2.6 Mha) in 1940 and 2.2% (3.2 Mha) in 2003. Area of harvested corn was 20.8% (31.0 Mha) in 1940 and 20.4% (28.8 Mha) in 2003 (NASS, 2004).

Cropland Practices to Sequester C

The net amount of SOC present is a function of the quantity and composition of crop residues, plant roots, and other organic material added or returned to the soil and the rate of SOC decomposition and loss by soil erosion and leaching of dissolved organic C from the soil. As described by Follett (2001b) plant C enters the SOC pool as plant "litter," root material, and root exudates or, if consumed by animals, as excreta. Litter-sized plant material abrades into smaller sizes (i.e., "light fraction" or "particulate organic matter"). These processes are mostly near the soil surface and therefore the C that is accumulating is easily lost as a result of soil erosion or increased tillage intensity. Some of the C and essential elements in these fractions become a source of nutrition for soil flora and fauna, including bacteria, fungi, and micro- and macro-fauna. Adsorption of organic material onto the reactive surfaces of clay minerals in soils and other clay particle surfaces is an important mechanism for binding soil particles together into soil aggregates. Among the organic materials

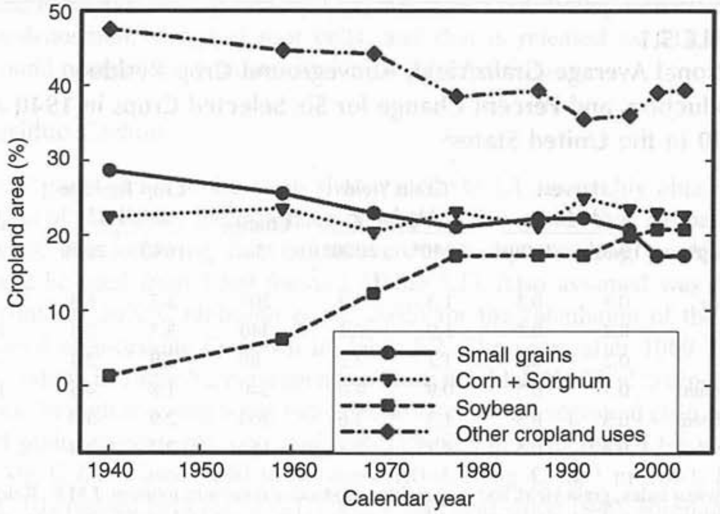

FIGURE 5.4 Fraction of U.S. cropland area on which small grain (wheat, rye, oats, and barley), corn plus sorghum, and soybean were harvested and area of other cropland used for crops from 1940–2003. Because of availability of data, 1997 values for cropland area are used as estimates for 2000 and 2003. (From National Agricultural Statistics Service (NASS), Agricultural Statistics, NASS of USDA, U.S. Government Printing Office, Washington D.C., pp. IX–6, 2004. With permission.)

important to soil aggregation are extracellular polysaccharides that soil microorganisms produce as a metabolic product while decomposing various organic substances. Polysaccharide molecules can be adsorbed to clay surfaces strongly through polyvalent bridging and because of the net negative charge that results from the presence of various organic acids (Chenu, 1995). Uncharged polysaccharides may strongly adsorb to mineral surfaces because of hydrogen bonding or van der Waals forces (Golchin, Baldock, and Oades, 1998).

Crop Yield and Residue Production

Changes in crop yields over time are highly important to the discussion of soil C because they can be related to changes in the amounts of crop residues and crop residue C available to return to the soil surface or incorporated into the soil. Recent and historical yield data are readily available through USDA-National Agricultural Statistic Service (NASS). Therefore, the C input from crop residues can be estimated using a "harvest index" (HI) equation (Donald and Hamblin, 1976; Hay, 1995) in which the crop residue (Yr) is estimated as:

$$Yr = Ygr\ [(1/HI)\text{-}1] \quad (5.1)$$

where Ygr is the harvested grain (or other biomass) and HI is the ratio of Ygr and aboveground crop residue yield. The HI, grain yield, and crop residue yields listed

TABLE 5.1
National Average Grain Yield, Aboveground Crop Residue Production, and Percent Change for Six Selected Crops in 1940 and 2000 in the United States[a]

	Harvest Index		Grain Yield (Mg ha^{-1})[c]		Change	Crop Residue (Mg ha^{-1})		Change
Crop[b]	1940[f]	2000[g]	1940[d]	2000[e]	%	1940	2000	%
Barley	0.3	0.5	1.3	3.9	200	3.5	3.9	40
Corn	0.4	0.5	1.9	8.4	340	3.5	7.5	110
Oat	0.2	0.4	1.2	2.2	80	3.9	2.8	–30
Sorghum	0.3	0.5	0.9	4.0	340	1.8	4.5	150
Soybean	0.3	0.5	1.3	2.6	100	2.9	3.0	5
Wheat	0.3	0.5	1.1	2.8	150	2.7	3.4	30

[a] Harvest index, grain yield, and crop residue production data from Johnson, J.M.F., Reicosky, D.C., Allmaras, R.R., Sauer, T.J., Venterea, R.T., and Dell, C.J., *Soil Tillage Res.*, 83, 73–94, 2005. With permission.

[b] Botanical names: Barley (*H. vulgare* L.), corn (*Z. mays* L.), oat (*A. sativa* L.), sorghum, soybean (*G. max* L. Merrill), wheat (*Triticum* ssp.).

[c] Three-year average centered on the shown year.

[d] From Cochrane, W., *The Development of American Agriculture: A Historical Analysis*, 2nd ed. University of Minnesota Press, Minneapolis, MN, 1993. With permission.

[e] From National Agricultural Statistics Service (NASS), Agricultural Statistics, NASS of USDA, U.S. Government Printing Office, Washington D.C., pp. IX–6, 2004. With permission.

[f] From Allmaras, R.R., Wilkins, D.E., Burnside, O.C., and Mulla, D.J., Agricultural technology and adoption of conservation practices, in *Advanced Soil Water Conservation*, Pierce, F.J. and Frye, W.W., eds., Sleeping Bear Press, Chelsea, MI, 1998, 99–157. With permission.

[g] From Lynch, P.J. and Frey, K.J., *Crop Science*, 33, 984–988, 1993; Prince, S.D., Haskett, J., Steiningfr, M., Strand, H., and Wright, R., *Ecological Appl.*, 11(4), 1194–1205, 2001; Halvorson, A.D., Peterson, G.A., and Reule, C.A., *Agron. J.*, 94, 1429–1436, 2002; Pedersen, P., Boote, K.J., Jones, J.W., and Lauer, J.G., *Agron. J.*, 96, 556–564, 2004; Vetsch, J.A. and Randall, G.W., *Agron. J.*, 96, 502–509, 2004; and Yang, H.S., Dohermann, A., Lindquist, J.L., Walters, D.T., Arkebauer, T.J., and Cassman, K.G., *Field Crops Res.*, 87, 131–154, 2004. With permission.

in Table 5.1 were recently reported by Johnson et al. (2005). The percent change in grain yields is attributable to genetic improvements, better fertility and pest management, and technological advances in soil management. The largest percentage change in grain yields were observed for corn and sorghum followed by barley, wheat, and soybean with oat having the least percent change. The calculated percentage increase of crop residue yields (i.e., vegetative aboveground biomass) was always less than for grain. The largest change in crop residue yield was exhibited by sorghum, followed by corn, barley, wheat, and soybean, with a decrease for oats Table 5.1. In terms of SOC contribution, aboveground vegetative biomass is only a portion of the total C input to soil by plants. To understand the soil C cycle, one must have a complete understanding of the plant C partitioned belowground that is transferred to support root growth and maintenance, contributing to root exudation and rhizodeposition, sloughed root cells, and that is released as CO_2 from the belowground respiration of plant roots and microorganisms.

Crop Residue Carbon

The annual grain yields of the crops shown in Table 5.1 are readily obtained from NASS. Use of HI allows the estimates of crop residue yields that are based upon grain yields. The following calculations were made by assuming that the HI for 2000 could be used from 1969 forward (Table 5.1). Also assumed was that crop residue contains 40% C (Johnson et al., 2005) for the calculation of the rates of aboveground crop-residue C shown in Table 5.2. The years after 1969 that were selected to show in Table 5.2 correspond to those in which NASS also reported land utilization. Though showing some increases in rates of aboveground crop residue C are small grains (wheat, rye, oats and barley) which have increased from between 0.8–2.0 Mg C ha^{-1} since 1940 to between 1.0–1.4 Mg C ha^{-1} in 2003. Soybean residue C has ranged between 0.7–1.1 Mg C ha^{-1} and since 1940, sorghum values have ranged between 1.3–1.8 Mg C ha^{-1}. The change and size of the rates of crop residue C production for corn have increased most rapidly since 1940 with corn residue C calculated to have increased from 2.1–3.6 Mg C ha^{-1}.

Multiplication of the calculated rate of crop residue C produced in the United States (Table 5.2) by area of harvested cropland area (Table 5.3) for each crop results in an estimate of total aboveground crop residue C production (Table 5.4). The last column in Table 5.3 shows how the total percentage of U.S. cropland used by these seven crops has changed between the years 1940 and 2003, ranging from 52% in 1940 to 64% in 1992. The final column in Table 5.4 shows the change over years in the calculated production of aboveground crop residue C by these seven crops. Comparison of the final columns in Table 5.3 and Table 5.4 shows that since 1987, very little change has occurred in the percent of cropland use, but that since 1992, greater than 20% more crop residue C has been produced than during or before

TABLE 5.2
Average Aboveground Residue C Produced (Mg C ha^{-1}) by Seven U.S. Crops

	Mg C ha^{-1}						
Year	Wheat	Rye	Oat	Barley	Corn	Sorghum	Soybean
1940	0.96	1.24	2.02	1.15	1.09	0.79	1.02
1969	0.82	0.88	1.15	0.96	2.10	1.36	0.74
1978	0.84	0.98	1.12	1.06	2.53	1.37	0.79
1987	1.01	1.10	1.17	1.13	3.01	1.74	0.91
1992	1.06	1.10	1.41	1.34	3.30	1.82	1.01
1997	1.06	0.97	1.28	1.25	3.18	1.74	1.05
2000	1.13	1.06	1.38	1.31	3.43	1.53	1.02
2003	1.19	1.03	1.40	1.27	3.57	1.32	0.90

TABLE 5.3
Total Area of Harvested Cropland (Mha) of Seven U.S. Crops and as a Fraction of the Total U.S. Cropland Used for Crops

	Mha							% of U.S.
Year	Wheat	Rye	Oat	Barley	Corn	Sorghum	Soybean	Cropland
1940	21.58	1.30	14.35	5.48	30.96	2.58	1.95	52.46
1969	19.27	0.55	7.26	3.86	22.11	5.48	16.60	55.70
1978	22.88	0.38	4.51	3.75	29.13	5.43	25.78	61.46
1987	22.66	0.27	2.79	4.03	24.10	4.27	23.15	60.65
1992	25.43	0.16	1.82	2.95	29.19	4.88	23.58	64.49
1997[a]	25.45	0.13	1.14	2.51	29.43	3.71	27.99	63.98
2000[a]	21.09	0.12	0.94	2.11	29.34	3.13	29.33	60.93
2003[a]	21.40	0.14	0.90	1.90	28.81	3.16	29.29	60.61

[a] The 2000 and 2003 U.S. cropland area used for crops is the same as in 1997.

TABLE 5.4
Calculated Aboveground U.S. Crop Residue C Production (MMg C) of Seven Major Crops

	MMg C							
Year	Wheat	Rye	Oat	Barley	Corn	Sorghum	Soybean	Total
1940	20.70	1.61	28.96	6.32	33.67	2.04	1.98	95.29
1969	15.85	0.48	8.39	3.71	46.54	7.46	12.22	94.66
1978	19.31	0.37	5.07	3.96	73.82	7.43	20.38	130.33
1987	22.96	0.30	3.26	4.54	72.43	7.43	21.10	132.02
1992	26.86	0.17	2.56	3.97	96.30	8.89	23.84	162.59
1997	27.02	0.12	1.46	3.14	93.55	6.44	29.27	161.00
2000	23.80	0.13	1.30	2.77	100.76	4.78	30.03	163.59
2003	25.43	0.14	1.26	2.40	102.78	4.18	26.30	162.49

1987. Although there has been a slight increase in residue C produced after 1992 and that it has been produced on a slightly smaller percent of the U.S. cropland area used for crops, the changes have been small. If these recent trends continue and alternate uses emerge to that of returning crop residues to the land then remaining crop residues must more effectively be used to sustain SOM, prevent soil degradation, and maintain environmental benefits of soil C while obtaining additional economic benefits.

Alternative uses of residues, especially on fragile lands, not only can refer to removal for biofuel, but also to such alternative uses as winter grazing of corn stocks by livestock. Recent data of the authors on a sandy soil site where, because of the fragile nature of the soil, conventional tillage treatments were being compared with strip tillage under full irrigation. The kg SOC in the top 15 cm, without winter

TABLE 5.5
The Effect of Using Cattle for Winter Grazing of Corn Residues during the Fall and Winter of 2003/2004 and the Fall and Winter of 2004/2005[a,b]

	Soil Organic Carbon in 0–5 cm			
	% C		(kg SOC ha^{-1})	
Treatment	**2003**	**2005**	**2003**	**2005**
Strip tillage	1.34a	1.23a, b	8160a	7860a
Conventional tillage	1.17a, b	1.07b	6800a, b	6050b
	Soil Organic Carbon in 5–10 cm			
	% C		(kg SOC ha^{-1})	
Strip tillage	0.66a	0.61a	7820a	7077a, b
Conventional tillage	0.60a, b	0.55b	6530b	6740b
	Soil Organic Carbon in top 10–30 cm			
	% C		(kg SOC ha^{-1})	
Strip tillage	0.66a	0.61a	17,650a	16,710a, b
Conventional tillage	0.60a, b	0.55b	16,130a, b	15,380b

[a] Cornstalks were not grazed, but remained on the field during the non-growing seasons of 2001 and 2002.
[b] Numbers followed by different letters are significantly different at the 95% confidence level.

grazing of corn stalks was stable or increasing through the spring of 2003. However, during the fall and winter of 2003/2004 and 2004/2005, a decision was made by farm management (without consultation with the researchers) to winter graze the corn stalks (at about 65 animal days/ha). As seen in Table 5.5, both the percent soil C and the weight of SOC decreased from 2003–2005. Average SOC under strip tillage had increased from 17,560 kg SOC ha^{-1} in the top 15 cm of soil to 20,390 kg SOC ha^{-1} by 2003 (or 33,630 kg SOC ha^{-1} in the top 30 cm). The corresponding values for the conventional tillage were a change from 17,600 kg SOC ha^{-1} in the top 15cm of soil to 17,540 kg SOC ha^{-1} to 17,540 by 2003 (or 29,460 kg SOC ha^{-1} in the top 30 cm). By 2005, the amounts of SOC measured in the top 30cm of soil were 31,650 kg SOC ha^{-1} and 28,170 kg SOC ha^{-1} for the strip and conventional tillage treatments, respectively. Table 5.5 shows the changes in both percent and weight of SOC for the three soil depth increments sampled and with both treatments generally being negatively affected. It should be pointed out that if residues are to be winter grazed the soils should not be fragile and susceptible to wind erosion and there may be need to improve the feed quality of the crop residues and not just the grain yields.

Crop Residues and Biofuels

Various authors are addressing issues associated with the production of ethanol from corn grain or biodiesel from soybean oil or other uses (such as the production of complex sugars for making of fabrics and biodegradable plastics) and the associated energy inputs. It is not the intent of this paper to evaluate the use of grain for the production of biofuel other uses, the interested reader is referred information included in articles by Shapouri et al. (2002, 2004), Pimental and Patzek (2005), Perlack et al. (2005), and Parfit and Leen (2005). Shapouri et al. (2002, 2004) generally indicate a net positive energy balance for the production of ethanol or biodiesel from grain whereas Pimental and Patzek (2005) contend that growing corn for ethanol results in a net negative energy balance while growing soybeans for biodiesel had a slightly negative energy balance. Interesting is that the corn grain contains 44% C and ethanol is approximately 52% C by weight. Thus, in general, the production of ethanol from grain results in a C density increase from 44–52% and the production of a C energy source that is in liquid form for use in motor vehicles. Energy inputs for the production of corn grain and its conversion to ethanol include inputs such as natural gas, diesel, electricity (including that produced from coal), and other C derived inputs. These energy inputs also express the economic and societal benefits of C; however, they include energy derived from fossil fuels that, when burned, result in an increased burden of fossil fuel derived CO_2-C being added to the atmospheric. By comparison, when CO_2-C is released from the direct burning of recently photosynthesized plant-derived biomass, it is recycled and adds little or no additional fossil C into the atmosphere.

Perlack et al. (2005) project that currently available biomass resources, using sustainable management technologies and with 40% recovery potential, is about 176 MMg dry tons annually; including 68 MMg from corn and 15 MMg from wheat and other small grains for a total of 83 MMg from these crops. Manures were estimated to provide an additional 32 MMg. If these residues are estimated to contain approximately 40% C, then they provide 27, 6, and 13 MMg residue C from corn, small grains, and manure, respectively (total 46 MMg), or about 65% of the total C from agriculture. Projected moderate (60% residue recovery)- and high (75% residue recovery)-yield increases resulting from technology with no land use change by 2014 are that 383 and 541 MMg of residues (153 and 216 MMg C) will be available, respectively. Of the residues projected to be available by 2014 for the moderate and high yield scenario, corn and small grains are projected to provide about 52 and 56%, respectively, and CRP lands are projected to provide perhaps as much as 5% of the total available residue. Perennial crops (grasses and trees) were not considered in the preceding scenarios, but when they are considered, they add large amounts of harvested biomass and C to the projections.

Serious questions were raised in a series of journal articles in 1979 about how much residue could be removed from the land without exceeding soil erosion tolerance limits. Larson (1979) summarized these data with the conclusion that crop residues could be available for energy production if the calculated erosion rates did not exceed the soil tolerance limit. With 1979 practices, there would be 49 MMg of residues available within the U.S. Corn Belt (36% of the residue produced in the region), and 65% of the residues would come from only 4 (of 14) major land resource areas that have relatively level, deep soils. In the Great Plains, about 16 MMg of residues could be harvested for energy and were produced in the more humid, eastern section. If both wind and water erosion was considered, available residue in the Great Plains was less (Skidmore, Kumar, and Larson, 1979). In Oregon, 60% of the residues could be harvested from 88% of the area planted to small grains, or about 1 MMg (Allmaras et al., 1979). In the Southeast United States, about 4 MMg of residue could be available (Campbell et al., 1979). The residues discussed in these 1979 articles are largely harvested from land planted to corn or small grains and their 1979 total was about 70 MMg. The weight of crop residue from corn and small grains projected by Perlack et al. (2005) is about 83 MMg or about 118% larger than projected in 1979. By comparison, data in Table 5.4 for 1987 and 2003 lists residue production by corn and small grains to be 103 and 132 MMg, respectively, or an increase of about 127%. The question remains whether adequate technology is available and will be used to sustain soil productivity associated with SOC in mineral soils when crop residue C is removed to produce energy. Focused research is needed on soil management, such as increased use of no-till (NT) or other practices to adequately protect SOC levels. Not addressed in this crop biomass discussion is the important role of belowground biomass C and whether, as aboveground yields increase, the belowground biomass is also increasing and how soil management may also contribute to the utilization of these residues as a resource to aid in the maintenance of SOC. Definitive studies are greatly needed about amount of C derived from root material and other below-ground inputs, their contribution to maintaining or increasing SOC, and the effects of the environment and soil management on them.

The choice of at least corn to be a potential residue crop may also be supported by the Tollenaar and Lee (2002) estimate of potential corn yields of 25 Mg ha^{-1}. From data on improved hybrids during 1930–2000 in the central United States, Duvick (1992, 2005) reported that corn grain yield and presumably increases in aboveground corn biomass yields had much higher limits than are currently observed. Corn grain and corn residue yields (Table 5.4) have increased dramatically during the past 60 years and even with continued yield increase, there is need for an increased application of advanced soil and residue management practices in the future. However, the optimistic estimates of increasingly larger corn yields must be tempered with the reality of the role of weather variability, soil, and other limitations to potential yields.

Cover Crops

"Cover crops" protect the soil from erosion and losses of nutrients via leaching and runoff. The term "winter cover crop" is used for a cover crop grown to protect the soil during the winter fallow period. Despite its acceptance, a winter cover crop does not necessarily need to be used during winter and can be used even during summer

(Delgado, Reeves, and Follett, 2004). If a legume is used, it can also potentially fix atmospheric N_2, and enhance soil N reserves (Power, Follett, and Carlson, 1983). Thus, the definition of winter cover crops can be expanded to those crops that are grown for improving soil, air and water conservation and quality; nutrient scavenging, cycling and management; increasing beneficial insects in integrated pest; and for short-term (e.g., over-winter) for animal-cropping grazing systems (Delgado, Reeves, and Follett, 2004; Reeves, 1994). Strategies that increase the cropping intensity such as the use of rotations with winter cover crops to increase the amount of biomass C returned to the soil can affect the size, turnover, and vertical distribution of both active and passive pools of SOC (Franzluebbers, Hons, and Zuberer, 1994). Winter cover crops can be an excellent source of forage for grazing for animals and can contribute to the development of sustainable animal-cropping systems. If suited to the climate and the farming operation, such cropping systems should provide an opportunity to produce more biomass C than in a monoculture system and to thus increase SOC sequestration. Winter cover crops are a viable tool for soil and water conservation. Lal et al. (1998) reviewed the literature on this topic and concluded that the potential exists for adopting winter cover-crop rotation systems on about 51 Mha, which could sequester an additional 100–300 kg C ha^{-1} yr^{-1}, thus resulting in 5.1–15.3 MMg C yr^{-1}.

Livestock Manure

Animal manure represents a valuable resource, and its potential for use as a feedstock for biofuel was briefly mentioned earlier and is discussed in more detail by Perlack et al. (2005). Additionally, manure use in many ways results in similar issues to those of other organic wastes. Consequently, though this discussion will be directed toward livestock manure the reader is asked to recognize this section in the broader context of organic wastes in general. Livestock manure and other organic wastes (assuming they do not have hazardous substances in them) have many beneficial effects, including on soil C sequestration. Organic wastes from a collectible source, such as manure from "confined" livestock operations, can be collected, stored, and made available for use as a nutrient resource, soil amendment, or for bioenergy generation. Livestock categories of manure include those from dairy (i.e., milk cows and heifers) or beef (i.e., steers, bulls, calves, and cows) cattle (*Bos taurus*); swine (i.e., growers and breeders) (*Sus scrofa domesticus*); chickens (i.e., broilers and layers) (*Gallus gallus domesticus*); and turkeys (*Meleagris gallopavo*) (NASS, 2004). Calculations were made by Follett (2001a), using procedures described by Lander, Moffitt, and Alt (1998), of the annual weight of manure N produced by confined livestock in those regions of the United States, where the manure can economically be applied to cropland. Next, an estimate was made that an average application rate equivalent to 250 kg N ha^{-1} yr^{1} could be made to 18 Mha of cropland with the manure produced. The application of the manure, as described previously, would result in sequestration at the rate of 200–500 kg C ha^{-1} yr^{-1}, thus resulting in an estimated sequestration of 3.6–9.0 MMg C yr^{-1} (Follett, 2001a).

U.S. GRAZING LANDS

Grazing lands represent the largest and most diverse single land resource in the United States. They include the relatively undisturbed rangelands of the West (i.e., grasslands, savannas, and shrublands) and the intensively managed pastures that occur in every state, including those of the humid southeast. Studies on croplands have monitored changes in soil C contents in response to management for over a century. Yet, data on grazing land responses of soil C to use and management are sparse. Only recently have scientists begun to document soil C contents and study C dynamics on grazing lands maintained for many decades under different management regimes. According to the Natural Resources Conservation Service of USDA (NRCS), privately owned rangelands and pastures in the U.S. comprise a total of 212 Mha (USDA-NRCS, 1994). Much of the 124 Mha of publicly owned lands in the western United States properly are classified as grazing lands. Millions of additional hectares of cropland throughout the nation are planted to forage, and these forages often are grazed as well as hayed or harvested as other forms of stored forage. Grazing lands are highly important for the production of meat and other animal products. They are also important for atmospheric CO_2-C sequestration because of the magnitude of the land area involved. Even if rates of C storage are low on an aerial basis, or maximum amounts of storage are limited and slowly attained, the total mass is large. Some portion of our grazing lands, like the arid rangelands in the West, may only be capable of small additional increases of C storage because of low seasonal productivity and shallow soils. Nevertheless, other areas, even some in the West, are highly productive and have deep, well-developed soils. Annual production of plant biomass on many native perennial grasslands and most pastures exceeds that of croplands, and intensively managed pastures planted to annual grasses or legumes on deep soils might store C at rates equal to those of annual crops in many regions. Some of the highest rates of C storage found in the scientific literature were measured on perennial grass pastures, especially after establishment on former cropland, even when the stands were not managed for high productivity but were left undisturbed, as are lands enrolled in the CRP.

Historical Perspective

Numerous accounts were recorded in the journals and records of early European travelers of U.S. grazing lands before European settlement. Hart and Hart (1997) traced some of the early records that extend from early explorers, including Coronado who traveled through Texas and possibly into Colorado from 1540–1542 and Trudeau, a trader on the upper Missouri from 1803–1805, to the present day. Estimates of the numbers of bison in the Great Plains based on work by Cushman and Jones (1998) and Shaw (1995) indicate there were from 15–30 million head. By comparison, in 2002, there were over 46 million head of cattle and nearly 400,000 head of sheep in the 10 Great Plains states (NASS, 2004). Johnson (1994) recorded that trees along the Platte River near Kearney, Nebraska were rare even up until 1938, but have increased greatly since. Lewis and Clark (Moulton and Dunley, 1983) recorded that the Missouri river was bordered by timber or brush for much of its length though the surrounding prairie was treeless. W.A. Bell, an early traveler, wrote of the area west of Salina, Kansas: "... as settlers advance,... domestic herds take the place of the big game... ". Box (1979) indicates that within twenty years after the first European settlers established a livestock industry the rangelands were overgrazed both in the humid Southeast and in the arid West. Settlers and ranchers came west with an eternal optimism about the carrying capacity of the rangelands they encountered. An early quote at the time of early western rangeland settlement was,

> Men of every rank were eager to get into the cow business. In a short time, every acre of grass was stocked beyond its fullest capacity. Thousands of cattle and sheep were crowded on the ranges when half the number was too many. The grasses were entirely consumed; their very roots were trampled into the dust and destroyed." (Bentley, 1898)

Another quote from the *Desert News* is dated September 25, 1879:

> The wells are nearly all dried up and have to be dug deeper. At the present time, the prospect for next year is a gloomy one for all the farmers, and in fact all, for when the farmer is affected, all feel the effects. The stock raisers here are all preparing to drive their stock to where there is something to eat. This country, which was once one of the best ranges for stock in the Territory, is now among the poorest; the myriads of sheep that have been herded here for the past few years, have almost entirely destroyed our range.

To summarize, early accounts often conflicted. Hart and Hart (1997) from their rather extensive review of journals and other records of early travelers conclude that, much of the Great Plains before European settlement looked about like it does now. The pronghorn have returned, but cattle have replaced the buffalo. The major changes have been produced by cropland agriculture and urbanization. Finally, the vegetation on the Plains will continue to change as it has throughout the Holocene, wherein parts of the northern Great Plains were forested as little as 10,000 years ago (Dix, 1962) and warm season grasses spread from south to north during the Holocene (Follett et al., 2004; Leavitt et al., 2007). During this large and important time span of wide climatic fluctuations (summarized by Follett et al. 2004), there were droughts, widespread aeolian soil movement, and both widespread climatic warming and cooling during which the sequestration of SOC must also have changed dramatically at various times. To the degree that European settlement has resulted in the degradation or improvements to the condition of U.S. grasslands, it is from this point forward that present and future management will continue to either have beneficial or negative effects.

The Present

Following European settlement of grazing lands in the east and up until 1940, animal and cropland agriculture were strongly associated because of the need for draft animals for planting and harvesting of crops. The 1940 population was less than half of what it is today (U.S. Census Bureau, 2000) and was centered further east in more humid climates with much sparser populations further west. Consequently, much eastern grazing land use, in contrast to western grazing land use, was associated with agriculture largely for pasturage or forage harvest. Further west, the Dust Bowl not only devastated vast areas of croplands, but also grazing lands, lands broken for cropland, and reseeded grazing lands were greatly deteriorated because of the need for livestock feed and the economic needs of farmers and ranchers.

After 1940 and where suitable, more intensive management with appropriate technological inputs (e.g., improved forages, fertilizer and pesticide use, and grazing management) began to be used, resulting in greater productivity and higher potential for soil C sequestration. Box (1979) states,

> While I believe that American rangelands are in the best condition they have been in for a century, I do not intend to leave the impression that they are producing anywhere near their potential.... On the whole, the rangelands of this country have improved over the past few decades and will continue to improve in the future.

Recent national analyses of the potential for soil C sequestration on U.S. grazing lands indicate that substantial national rates exist (Follett et al., 2001a). Estimates are that grazing land sequesters nearly 37 MMg yr^{-1} and that an additional 21 MMg C yr^{-1} is sequestered through land conversion and restoration (not including CRP contributions). The roughly 330 Mha of nonintensively managed grazing land (federal and nonfederal) sequesters about 5 MMg C yr^{-1}, but 107 Mha of rangeland with improved management sequester 10 MMg C yr^{-1} and 36 Mha of improved pasture in the United States are estimated to sequester 14.8 MMg C yr^{-1}. On the negative side the combined effects of soil erosion (wind and water), acid precipitation, and fertilizer induced acidity to pastures are estimated to result in soil C losses of 16 MMg C yr^{-1} from as much as 239 Mha of grazing land soils in the United States. These data indicate that large areas of grazing lands exist that are sequestering C at very low levels and that significant soil C losses also occur, but that there is an overall net gain of 18–90 (avg. 54) MMg C yr^{-1}.

Based on 3 years (1995–1997) of CO_2 flux measurements representative of 51 Mha, Frank et al. (2001) estimated annual SOC rates at Mandan, ND, Woodward, OK, and Temple, TX, at 86, 87, and 459 kg C ha^{-1} yr^{-1}, respectively. These figures are similar to those of Schuman et al. (2001), who indicate that currently there are 107 Mha of private U.S. rangeland where improved management could sequester 50–150 kg C ha^{-1} yr^{-1} and even though the rates are low, the large area involved results in total sequestration estimates of 5.4–16.0 MMg C yr^{-1}. However, too little data on grazing land C sequestration rates have been collected in the United States and in most other regions of the World. Follett and Schuman (2005) report that the amount of meat produced from grazing animals, defined as being from beef, sheep, goat, and buffalo can be used as a metric to evaluate soil, climate, and management potential and the corresponding SOC sequestration rates across broad regions of the world. Table 5.6 shows the change in meat produced from cattle and sheep within the United States at the same time intervals as were reported in Tables 5.2, 5.3, and 5.4 (NASS various years). Based upon the Follett and Schuman (2005) report, a change in U.S. grazing animal meat production should reflect SOC sequestration on U.S. grazing lands. There is a steady increase in U.S. meat production with generally

TABLE 5.6
U.S. Production of Meat from Beef, Veal, Lamb and Mutton, and All Meats

	MMg Meat			
Year	**Beef**	**Veal**	**Lamb and Mutton**	**All Meats**
1940	3.26	0.44	0.40	8.66
1969	9.60	0.30	0.25	16.63
1978	11.00	0.29	0.14	17.51
1987	10.69	0.19	0.14	17.56
1992	10.53	0.15	0.16	18.69
1997	11.57	0.15	0.12	19.68
2000	12.21	0.10	0.11	21.02
2003	11.82	0.09	0.10	20.85

Source: From NASS 1948, 1972, 1985, and 2004.

more than half from beef but production of meat from veal and sheep has decreased during from 1940 on.

Rangeland grazing management systems have been developed to sustain efficient use of forage by livestock, but there is generally little accompanying understanding of the effects of grazing on the redistribution of and cycling of C and N within the soil plant system. The capacity of rangeland ecosystems to sequester SOC is an interaction among the spatial distribution of plant production, availability of soil and water resources, and management inputs. If management is targeted to those parts of the landscape that have higher resource availability, a high potential for enhanced productivity and C storage is more likely achieved. Management that adequately considers these factors, and if applied over a wide enough area, can potentially contribute to improved soil C sequestration, benefits to wildlife, decreased soil erosion, and to other potential social benefits associated with decreased adverse on- and off-site effects.

The majority of improved pastures in the United States are east of the Mississippi River. They occur on many soil types, with varying fertility, texture, and structure, and across a range of climatic conditions. Each of these soil properties and climatic factors has important, generally predictable effects. Overall, temperature and moisture are the most important climatic factors for determining soil C dynamics because of their effects on potential net primary productivity (NPP) and soil microbial activity. Schnabel et al. (2001) indicate that pastureland in the United States include 51 Mha of improved, native, and naturalized pastures. In the northeastern and north central United States, the pasturelands include cropland pasture, improved pasture, woodland pasture, and other. Species of grasses included in pastures are Kentucky bluegrass (*Poa pratensis* L.), orchardgrass (*Dactylis glomerata* L.), timothy (*Phleum pratense* L.), and quackgrass (*Agropyron repens* L. Beauv.). Improvements include fertilization and liming and added legumes. In the north central United States, forage species are similar but include tall fescue (*Festuca arundinacea* Schreb.) in the southern portion and smooth bromegrass (*Bromus inermus* L.) in the northern and central parts. In the southeastern United States, grass species shift to predominantly warm season species such as bermudagrass (*Cynadon dactylon*), bahaigrass (*Paspalum notatum*), and dallisgrass (*Paspalum dilatatum* Poir.) Several clovers frequently are planted as winter annual pastures or on prepared seedbeds or sod-seeded into dormant warm season grass sods. Types of management input for increased rates of SOC sequestration are improved nutrient management, plant species, and grazing systems on pasture soils. It was observed by Follett, Kimble, and Lal (2001a) that nearly 8 additional MMg C yr^{-1} could be sequestered through more intensive or improved management on 21 Mha of pasture (average 0.4 MMg C yr^{-1} more) with the improved systems. Continued improvements in forage species through plant breeding programs and the adoption of improved grazing and fertility management practices under these more humid climates should allow continued future gains in rates and amounts of SOC sequestered.

Future Considerations

Managers and policy makers need more effective information describing the potential for grazing lands to sequester C and how improvements in the science and technology can increase C sequestration through appropriate inputs and management. A policy aspect related to grazing lands are the large C stocks they contain and that if some significant part were returned to the atmosphere as CO_2, it would add considerably to the atmospheric greenhouse warming potential (GWP). Soil stocks to a 1-m depth were measured across the U.S. Great Plains and averaged from 80–90 Mg SOC ha^{-1}, not including soil inorganic C (SIC) (Follett et al., 2001b).

A concern to C sequestration on grazing land associated with global climate change is warming global temperatures. Parton et al. (2001) identify that the major factors affecting grassland soil C levels are soil texture, decomposition rates, and C input to the soil. Their modeling work to assess climate change, which included the impact of probable increases in atmospheric CO_2 on plant growth, was done for the U.S. Great Plains. Their simulated changes in soil C levels between 1980–2050 under the Hedley Centre Transient Global Circulation Model climate change scenario provides some assurance that large amounts of CO_2 will not be discharged into the atmosphere from the degradation of existing SOC and, although soil C might decrease to the North, it suggests that soil C sequestration might show an overall slight increase for the Great Plains (Parton et al., 2001).

ECONOMIC AND SOCIETAL CONSIDERATIONS

The Current Situation

As reported by Lal et al. (1998), Bruce et al. (1999), and other authors, practices that increase residue or plant growth result in enhanced SOC sequestration. Such increases also are associated with the production of C contained in food, feed, and fiber. Alternative uses of plant photosynthesized C products, such as their use for biofuels, are currently occurring or are being increasingly evaluated. Use of conservation tillage (i.e., no-till, ridge-till, and mulch-tillage), maintaining higher levels of residue cover on conventionally tilled cropland, planting cropland to permanent cover (i.e., the CRP), and improved fertility management help protect soil and increase SOC sequestration (Lal et al., 1998). Conversely, practices that remove excessive amounts of vegetation or plant residues (i.e., fallow, plow tillage, and abusive grazing practices) usually cause soil erosion and result in SOC oxidation and loss.

A primary purpose of U.S. agriculture is to produce food and agricultural products. However, agricultural practices need to be environmentally friendly. There is increasing awareness of the role of agricultural in the emission of GHGs. Energy inputs required to power farm machinery, pump water for irrigation, manufacture fertilizers and pesticides, and transport farm products to market result in GHG emissions into the atmosphere. Besides CO_2, other GHGs resulting from agriculture activities are nitrous oxide (N_2O) and methane (CH_4). A major benefit of the use of RMPs in agriculture is that they help sequester atmospheric CO_2 in the form of SOC to offset the greenhouse warming effect of GHGs. This sequestration is a contribution by farming to the mitigation of global warming, and with the use of scientific agriculture, net beneficial effects can be larger than the negative effects. Atmospheric CO_2 concentration has increased by about 32% from pre-industrial levels (280–370 ppm) and U.S. GHG emissions gases for 2000 were estimated at approximately 1887 MMg CO_2-CE yr^{-1} (US EPA 2002). Using IPCC methodology to identify changes in net GHG emissions from 1990–2001, four of the larger agricultural sinks for CO_2 were identified as being due to the conversion of cropland to hayland, conversion of cropland to grazing land, the CRP, and from land application of manure (USDA, 2004). The two largest agricultural-land sources of atmospheric CO_2 from 1990–2001 were caused by plowout of grazing lands and cultivation of organic soils. Worth noting is that even though relatively small areas of organic soils are farmed in the United States, 60% of the SOC that is sequestered by minerals soils within the rest of the United States is needed to offset their CO_2 emissions (USDA, 2004).

The length of time that SOC sequestration rates continue after adoption of improved practices is uncertain. Eventually, a new steady state is approached as the losses of C from the soil start to equal the C additions to the SOC pool. As the new steady state is approached, it tends to be maintained until management, weather patterns, or other factors cause it to change. Estimates by Lal et al. (1998) are that achieving this practical limit may require at least 50 years, and Qian and Follett (2002) reported a continued increase for up to 30 years under grass. Thus, it might be assumed that most C sequestration increases resulting from management changes approach a new equilibrium in 25 years or more. This relationship affects the estimates of the U.S. rates of increase in SOC sequestration during long-time periods and limits the time during which U.S. agriculture can help offset the C emissions from other sectors of the U.S. economy. Thus, agriculture provides a window of opportunity for the other sectors to develop alternative technologies whereby their rates of CO_2 emissions can be decreased.

Societal Expectations of Agriculture

In the 1930s, 25% of the U.S. population lived on farms, now it is less than 2%. From a peak of 6.5 million farms in 1935, the number of farms decreased to 5.5

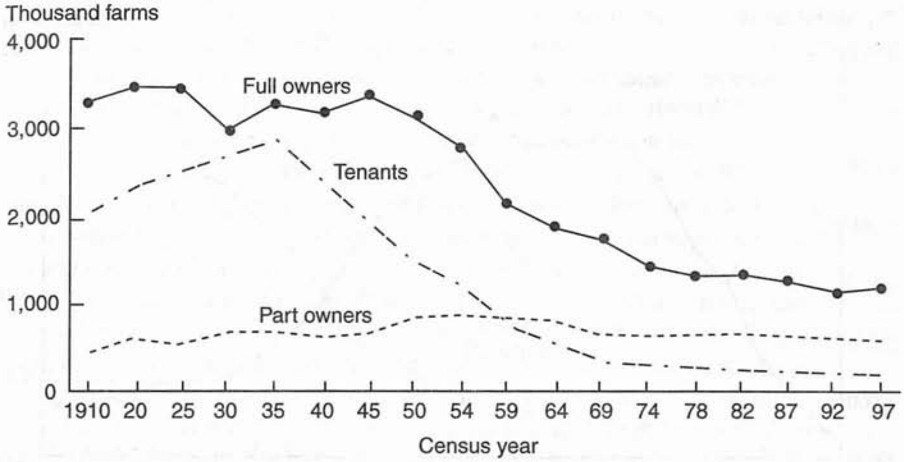

FIGURE 5.5 Number of family farms by tenure, 1910–1997. (From Hoppe, R.A., Ed., Structural and Financial Characteristics of U.S. Farms: 2001 Family Farm Report. Economic Research Service, USDA, Resource Economics Division Agriculture Information Bulletin No. 768, Washington, D.C., May 1, 2001. With permission.)

million in 1950, and by 1992 was only 1.9 million — less than in 1860 (Kime, 1996). The most rapid decline in number of farms began in approximately 1935 with most of the decline accounted for by full owners and tenants (Figure 5.5). The number of farms has since decreased, whereas the size of farms has increased (Figure 5.6). In 1996, 25% of the farms accounted for 88% of production. By another count in 1997, there were 2,190,510 farms remaining. Of these, 1,191,050 farms produced less than \$10,000, 645,960 farms produced \$10,000 to \$99,999, and 353,500 farms produced more than \$100,000. The largest operations (353,500 farms) controlled more than half of total U.S. farmland area.

Soil conservation is important for the protection of soil quality (including protection and increased sequestration of SOC). In addition, societal expectations increasingly include issues related to having clean water, high air quality (including low levels of particulates and odors), enhanced wildlife habitat, protection of or increased areas of wetlands and riparian vegetation, and finally minimal ecosystem impacts. These expectations can largely be associated with practices and approaches that protect or increase SOC in agricultural lands, or as more broadly identified to provide ecological services. Individual property rights, as currently defined, do not suffice to maintain, improve, or even provide ecological services for society's benefit. Manale (2001) identifies that many ecological services, such as floodwater retention or wildlife habitat protection, require management practices that extend beyond individual property boundaries. Intervention by agricultural programs may not necessarily be directed at the individual farm, but rather at restoring an ecological service at a broader geographic scale. Thus, the spatial scale needs to be expanded to encompass a broad range of technical and institutional options. It is not the intent here to discuss public policy options other than to point out as identified by Manale (2001) that

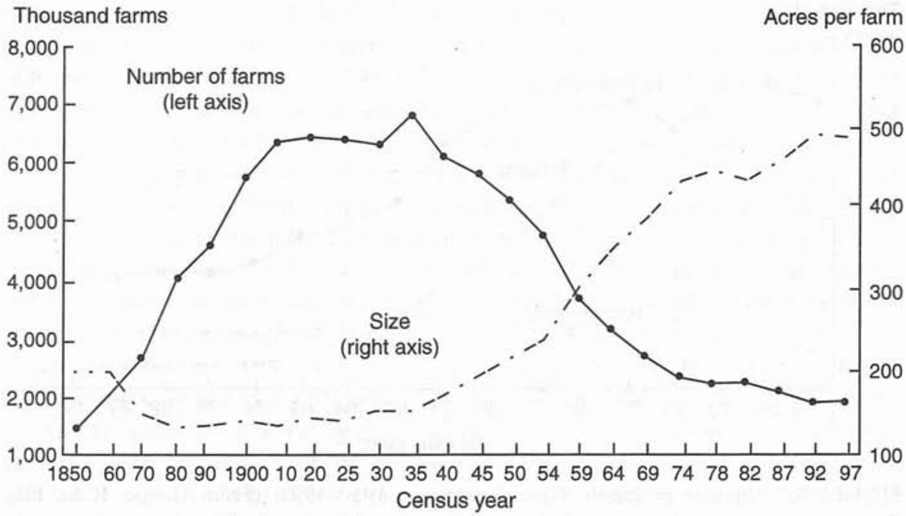

FIGURE 5.6 Number of farms and acres per farm 1850–1997. To convert acres to ha, multiply numbers on the right axis by 0.405. (From Hoppe, R.A., Ed., Structural and Financial Characteristics of U.S. Farms: 2001 Family Farm Report. Economic Research Service, USDA, Resource Economics Division Agriculture Information Bulletin No. 768, Washington, D.C., May 1, 2001. With permission.)

> Superimposed upon the effect of individual farming decisions on the environment are public policies and collective actions that exacerbate or amplify the magnitude of the impacts. In the United States and in most developed countries, government programs have historically affected how farmers farm or steward the land exacerbating agriculture's impact on the environment.... Agricultural programs that induce a bias toward intensive farming practices that boost yields, expand production onto marginal lands, and concentrate production on a small number of crops can undermine efforts to encourage adoption of conservation practices. Despite major changes in farm policy in the United States and Europe since 1989, the linkages between farm program support and production decisions remain.... Income-support programs in the United States under the 1996 farm bill, such as the commodity loan programs, influence producer decisions regarding the use of marginal lands, the intensity of land use, tillage practice, monocultural cropping practices and habitat protection...

The combined effects of items discussed previously point out how much is expected of a dwindling number of individual landowners in terms of America's expectations of them. Even though agricultural soils are important for SOC sequestration to reduce atmospheric CO_2 by improvements and by the use of RMPs, the key individuals who will make this happen will be the land managers (i.e., farmers and ranchers) as they adapt their management practices to accomplish better land stewardship. This improved management and the resulting increases in SOC is part of the emerging market in "environmental services" which supporters claim can harness market forces to provide economic incentives for environmental protection. Under the Kyoto Protocol, many developed nations have distributed tradable pollution rights to their major industries and are encouraging the trading of these rights by polluters in the electricity generation, oil, steel, cement, chemicals, pulp, and paper sectors to achieve compliance with their GHG reduction targets at lowest cost. The United States has not ratified the Protocol. At present, trading within the United States is voluntary, and regulatory measures have not been used to encourage corporations and other groups to reduce their net GHG emissions. Where trading has been more formally emplaced, it allows companies that are able to reduce their emissions beyond their stated goal to sell the extra reductions as credits on the market. Companies that cannot easily reduce their emissions can buy those credits to cover their reduction commitment. However, without a binding cap on GHG emissions, there is relatively little demand for C credits in the United States; the market for buying and selling the credits is very limited while the prices paid are low, including that for C sequestration in soils (Williams, Peterson, and Mooney, 2005). Concerns exist about the environmental effectiveness of C trading in the United States because it was established on a voluntary basis only. Still, the effort is an important step in pioneering programs to mitigate climate change. Even though considerable interest exists among agricultural producers, it is largely uneconomical for them to make major changes in their management practices to sell C credits. Management changes made by producers that are beneficial for C sequestration are most likely done to improve the efficiencies and cost savings for their operations or in response to incentives provided by government programs. Two examples where management changes have been made that encourage soil C sequestration, but yet are not specifically directed to do so include: (1) government programs that subsidize the use of certain practices such as CRP, and (2) the need for producers to improve efficiency and reduce input costs such as adoption of less intensive tillage to decrease fuel costs. Should U.S. policies toward C sequestration provide adequate incentives for producers to adopt RMPs to increase C sequestration, there is little doubt that major changes could occur. On the negative side of the soil C balance sheet may well be the diversion of crop residues to become biofuels. Little doubt exists that if the sale of crop residues and its removal from the land provide a reasonable income source for producers, then a potential loss or decreased levels of SOC sequestration could occur because of decreased return of residue C to the soil.

Numerous legislative bills, laws, policy statements, and other federal and local guidelines and rules over many years have been passed or otherwise expressed about the expectations from U.S. agriculture. What is often not identified in association with agricultural entitlement or subsidy programs is the maintenance of a cheap, plentiful, and nutritious food supply for American consumers. Certainly, the goal of maintaining low commodity prices as crops leave the farm gate has been achieved. For example, 40 years ago, a farmer purchased land for \$1235 ha^{-1} (\$500/acre), while the price of a bushel of corn was \$0.04 kg^{-1} (\$1.00/bushel). Today, the same farm ground is selling at approximately \$12,345 ha^{-1} (\$2000/acre), and the price of corn is \$0.07 kg^{-1} (\$1.80/bushel). The price for wheat that farmers are receiving today is the same price as in the year 1910. To survive, farmers have focused on the use of monocultures or simple rotations such as corn and soybeans (Power and Follett, 1987). Another result has been that because the prices that American farmers receive have not increased in the past three decades, the average annual exports usually stay between $40–50 billion. Exports of U.S. agricultural products once accounted for a huge dollar share (about 60%) of the total U.S. exports until the 1980s, but continual depressed prices have caused agricultural exports to slip in the rankings (now 5th) (NASS, 2004). Grain (and the C it contains) that was formerly exported to offset our balance of trade, and crop residue C that helps sustain and increase SOC, may now begin to help offset the cost of the large amounts of petroleum now being imported into the United States (Parfit and Leen, 2005) by their conversion to liquid fuels for motor vehicles (i.e., ethanol and biodiesel).

SUMMARY

There is a large potential for agricultural lands to produce large amounts of C based products (crops, residues, livestock, and forage). However, significant amounts of the C contained in crop residues and manures are needed to sequester SOC. In the future, there will be major challenges to obtaining the benefits of alternative uses crop residue C while also maintaining and enhancing levels of SOC and the environmental benefits associated with crop residue return to the soil to sequester SOC. In terms of privately owned lands, nearly 185 Mha of cropland and 212 Mha of grazing lands are available in the United States, which are operated by a decreasing and aging fraction of the U.S. population. A larger part of the overall U.S. production is occurring on fewer and larger farms, a widespread consolidation and specialization in agriculture is occurring, a shift away from combined crop and livestock systems is occurring, and an agricultural industry structure has developed wherein livestock feeding is in small geographic areas. The combination of these factors means that policy intervention, including economic incentives, is needed to sequester more soil C, encourage more efficient use of the nutrients in residues and manures, and capture those improvements that are consistent with economies of scale and increased efficiencies of production on large areas of U.S. agricultural land. Certainly, reduced tillage practices that require less energy inputs and seeding directly into largely undisturbed crop residues is consistent with enhancing SOC sequestration and with reducing fuel costs as well as recycling nutrients contained within the residues back into the soil for the next crop. Such practices also have the potential to conserve soil moisture. At least some, if not many, combinations of improved practices can be environmentally friendly, can contribute to SOC sequestration on agricultural lands, and can be economical and efficient enough to be suitable for larger as well as smaller operations. It will be important that practices that sustain the soil resource and efficiently use water and nutrient resources be increasingly used should U.S. agricultural lands be required to produce increasing amounts of grains and crop residues for biofuel to partially offset the large amounts of petroleum products currently imported by the United States.

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